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ORIGINAL ARTICLE

Crop improvements for future-proofing European food systems: A focus-group-driven analysis of agricultural production stakeholder priorities and viewpoints

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Abstract

Crop breeding is one of the main tools which can assist in future-proofing food systems for more sustainable outcomes. In order to ensure priorities are aligned with the needs and wants of food system actors, it is essential to engage with key stakeholders to understand preferences on plant breeding solutions. This study presents results from a series of online focus groups conducted with agricultural production related stakeholders (i.e. farmers and farmer representatives, policy-makers and NGOs) regarding the potential for crop improvement to future-proof European food systems. Stakeholders shared concern around climate change and environmental impacts (particularly drought and heat stress), and general agreement about the need to develop resilient crops which combine multiple positive attributes, while reducing trade-offs and negative externalities. Stakeholders also prioritized plant breeding solutions for areas where they felt they had little agency, and existing alternative solutions, such as improving input use efficiency, or altering diets to be considered where these are available. This highlights the need for the crop breeding community to focus its attentions on the 'most hard to fix' issues, where in-field measures are currently not offering viable solutions, to maximize acceptance and adoption by agricultural production stakeholders. It also highlights that consideration of trade-offs, within plant and within a broader agri-food context, must be integrated into crop breeding research and development, with trade-off analysis an explicit component of breeding research. Understanding broader agri-food system knock-on effects of plant innovation is a non-trivial challenge requiring interdisciplinary research and close partnerships with food system stakeholders.

KEYWORDS
focus groups, plant breeding, stakeholder engagement, sustainable food systems

1 | INTRODUCTION

The importance of the interlinked challenges regarding food security in the face of population growth and climate change are widely regarded as key global priorities (European Union, 2020; UN General Assembly, 2015). Climate change scenarios are anticipated which will see wide-spread climatic shifts, desertification and extreme weather events (IPCC, 2014), all of which will put pressure on food systems and crop production. Feeding 9.7 billion people by 2050 (United Nations, 2019) in a sustainable way will require changes at all stages of food systems, and integration of knowledge from a variety of different stakeholders and disciplines (Ingram, 2011; Willett et al., 2019). Future food systems must be resilient to climate shocks, while also producing sufficient quantities of nutritionally adequate foods, and maintaining or improving social and economic systems in order to provide sustainable outcomes.

One mechanism which could play a role in future-proofing our food systems is plant breeding with the aim of increasing sustainable crop production. Plant breeding research, using a variety of breeding techniques, is already well underway which aims to produce crops which require lower nitrogen inputs (Lammerts van Bueren & Struik, 2017), have higher yields (Takai et al., 2013), are able to cope with extreme weather events, such as droughts (Oladosu et al., 2019) or which provide additional nutritional benefits, such as increased micronutrient content (Welch & Graham, 2004). The CropBooster-P project is tasked with developing a roadmap for future-proofing European food systems and the bio-economy through plant breeding for environmental and social challenges, with a specific focus on three key goals: yield increase, nutritional content and other sustainability traits. Taking a Responsible Research and Innovation approach, the CropBooster-P project involves key stakeholders, including scientists, agribusinesses, seed and breeding sector representatives, farmers and farmer representatives, citizens, non-governmental organizations (NGOs) and policymakers, to align the process and its outcomes with the values, needs and expectations of society. As part of the CropBooster-P project, farmers, farmer representatives, NGO's working on environmental and agricultural issues and policymakers working in the agri-environmental domain were engaged in a series of focus groups to discuss the potential for plant breeding to future-proof European food systems. This paper presents the results of these discussions, with an analysis of the issues raised by participants which need to be taken into account by plant scientists and breeders in order to contribute towards integrated, sustainable food system outcomes.

2 | METHODS

2.1 | Cropboosting goals and options

Previous work in the CropBooster-P project identified a toolbox of potential "cropboosting" improvement options aimed at future-proofing European food systems, drawing on the state-of-the-art from the plant science community. In order to create a framework within which to guide focus group discussions, these options were grouped under the three overarching cropboosting goals of the project: increasing yield, nutritional quality and sustainability (see Figure 1 for a full list of the cropboosting options). We acknowledge that some options are interconnected and may deliver across two or more goals; however, this alignment to the goals provides a useful structure for communication with stakeholders.

In order to understand the potential impacts of different future-proofing strategies for European agriculture, a series of virtual focus groups were held with relevant stakeholders from across Europe. Ethical approval by Lancaster University Faculty of Science and

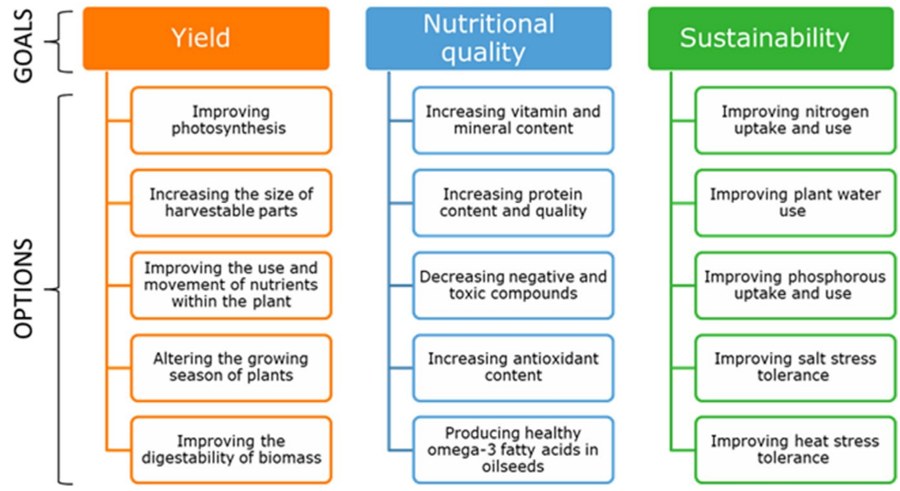

FIGURE 1 CropBoosting goals and options

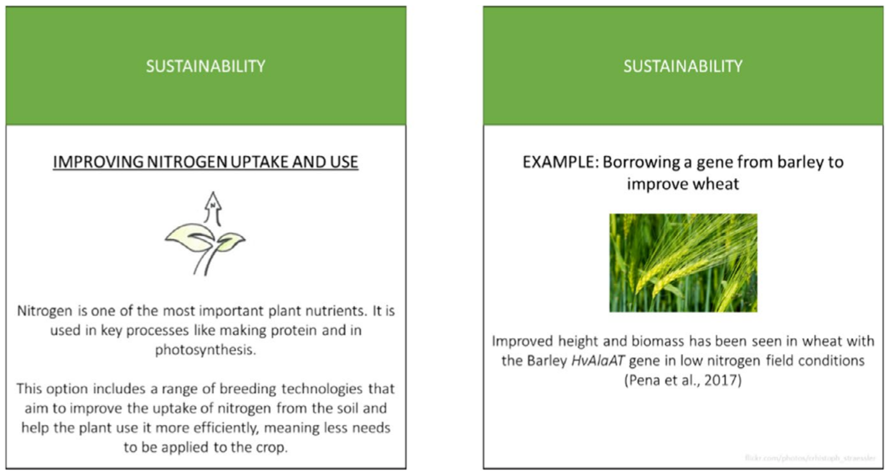

FIGURE 2 Example of option card. Front (Left) and Back (Right)

Technology Research Ethics Committee was granted (reference: FST19070), which outlined the overall protocols of the study, what types of data would be collected and how it would be managed. A topic-specialized researcher (SS) was assigned to coordinate, run and analyse the focus groups, with input from the wider project team.

To facilitate discussion and to present all the options to participants, the 15 CropBooster-P "options" for crop improvement were introduced on double-sided option cards, an example of which is given in Figure 2. These cards featured an indication of the broader aim in which they sat, an explanation of the option itself and a science-based example of this option applied to a real-world crop. In addition to the 15 option cards, a blank card – "Option Card #16" – was created in order to foster discussion about what potential crop improvement strategies could be added to the list (see Figure 3).

2.2 | Focus group protocol

Focus groups provide a mechanism that offers insights into the differences of opinion that exist among selected groups of people and generate a large amount of data in a relatively short period of time. Through the interaction between participants, focus groups are more likely to provide new ideas and support assessment of existing ideas (Breen, 2006; Rabiee, 2004). They were, thus, implemented in order to investigate a broad range of opinions on the various crop improvement options, their importance for future-proofing the European food system and key issues that should be considered in development and deployment of these crop innovations. A detailed semi-structured focus group protocol was created, pre-tested and piloted in-person in January 2020 and again after focus groups were adapted for online execution (see Menary et al., 2021) following COVID-19 travel restrictions in spring 2020 (for the full protocol, see Supplementary 1). The primary questions were as follows:

- What are the biggest challenges for the European agri-food sector over the next 30 years?
- Which cropboosting option is most important for each goal (Yield, Nutrition, Sustainability)?
- Which cropboosting option is least important for each goal (Yield, Nutrition, Sustainability)?

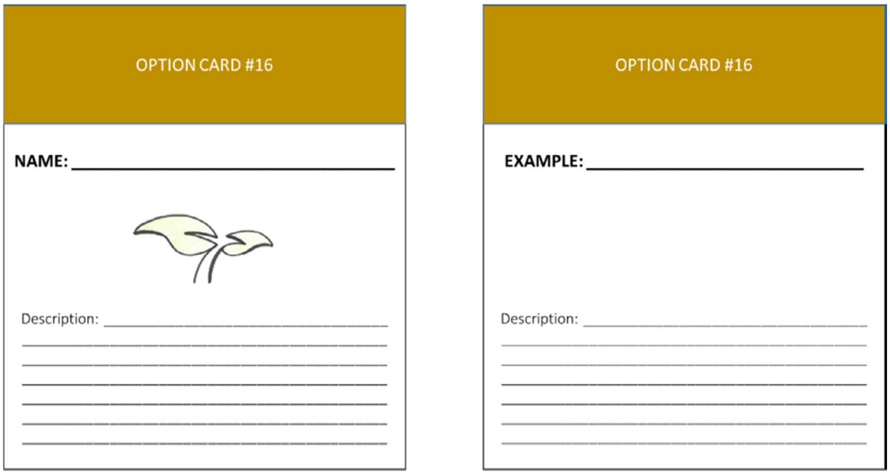

FIGURE 3 Option Card #16 Activity Card

- What might the social, environmental or economic impacts of a particular option be?
- How do these options meet the challenges facing the European agri-food sector?
- What other things should be included in the cropboosting options?

The online focus groups were hosted within *Microsoft Teams*, a secure platform the moderators were comfortable with and which provided the necessary functions of browser-only access and video recording. To facilitate working with different option cards, *Microsoft Teams* was combined with the website *Mural* (www.mural.co), which provides a platform for multi-person, interactive whiteboarding. The option cards and the Option Card #16 activity were incorporated into a Mural whiteboard. Multiple versions were created with different card orders to avoid ordering bias.

Purposive sampling among experts was the primary strategy applied. Additional suggestions as co-nomination from some participants were included as secondary (snowball sampling) strategy. Farmer representatives were first contacted via an online newsletter for COPA–COGECA – an agriculture umbrella organization bringing together farmers, farmer representatives and agricultural co-operatives from across Europe – in order to attract participants from a range of countries. Further representatives were contacted through the personal and professional relationships of the research team. Email invitations were sent to ten environmental regulators/European government bodies/policymakers/policy experts, and ten European NGO's working in the areas of environment, agriculture and/or sustainability – some snowball sampling was also used for these groups, as initial contacts shared the invitation within their networks or suggested alternative individuals/organizations.

2.3 | Focus group composition

Five focus groups took place between late April and early June 2020 with a total of 16 participants. Eleven farmers and/or farmer organization representatives took part in focus groups, with 12 initially responding to invitation and one non-attending – these 11 participants were grouped together at random (dependent only on participant availability) in three focus groups. In the case of NGO and policy representatives, of the 39 individuals who were approached, five took part in the focus groups with nine responding and four non-attending. The five NGO and policy representatives were grouped together at random in two focus groups.

The focus groups were convened by the lead researcher (SS), with back-up moderation and technical support available during the focus groups from JM and AN. All have experience with qualitative data collection. None had any pre-existing relationships with the participants. A standardized form was used to keep notes throughout the focus group. Focus groups totalled 8 hours and 35 minutes of audio recording that was transcribed verbatim.

Participants represented ten EU countries (Belgium, France, Germany, Italy, the Netherlands, Portugal, Romania, Spain, Sweden and the UK). Three focus groups focused on farmer representatives, of which a total of 11 where recruited from the membership of COPA–COGECA, representing six different European countries. Of these 11 participants, five were female and six were male. Two focus groups brought together those working in food policy with representatives from NGO's; a total of five participants were involved in these focus groups, two from policy and three from NGO's, representing five European countries. Of these five participants, three were female and two were male. Focus groups contained between two and four participants. Many participants had lived and worked in multiple European countries and brought insights from these multiple country perspectives to bear in the discussions.

2.4 | Analysis approach

The video recordings of each focus group were sent to a private GDPR-compliant company for transcription with a non-disclosure agreement signed in advance. Once the transcripts had been returned (60,640 words in total), these were checked for errors and anonymized by removing identifying information.

Adopting a Framework Analysis approach (Ritchie & Lewis, 2014; Srivastava & Thomson, 2009), an initial coding framework was developed by the lead researcher (SS) open coding the transcripts. After these were agreed through consultation with an additional member of the research group to reduce bias (JM), the transcripts were fully coded and analysed using NVivo12 qualitative data analysis software for Windows. An overview of the emergent themes was shared within the wider research authorship for comments, which helped to further refine the analysis framework for shared themes across the stakeholder groups – further analysis aimed to identify important differences between farmer representatives, NGOs and policy stakeholders' views.

Results from the focus groups were analysed together to present key stakeholder input, except where important differences exist between the perspectives put forward in the farmer representative and NGO/Policy stakeholder discussions. Key themes were differentiated from secondary themes based on a combination of factors, with key themes being mentioned in most or all focus group discussions, covered by participants from all three stakeholder subgroups, and generally discussed in-depth. While, in general, key themes were raised 30 or more times throughout the focus groups, importance cannot be solely determined by the number of times raised, hence, the additional criteria used. Conversely, secondary themes may have been covered in only one or two focus groups, raised by one or two stakeholder subgroups and/or mentioned relatively few times without significant depth in the discussion.

3 | RESULTS

A total of seven key themes and four secondary themes were identified from the focus groups (see Figure 4), each of which is described in detail in the following section and illustrated with quotes from the focus groups.

The seven themes were centred around the need to find practical solutions to build the resilience of the

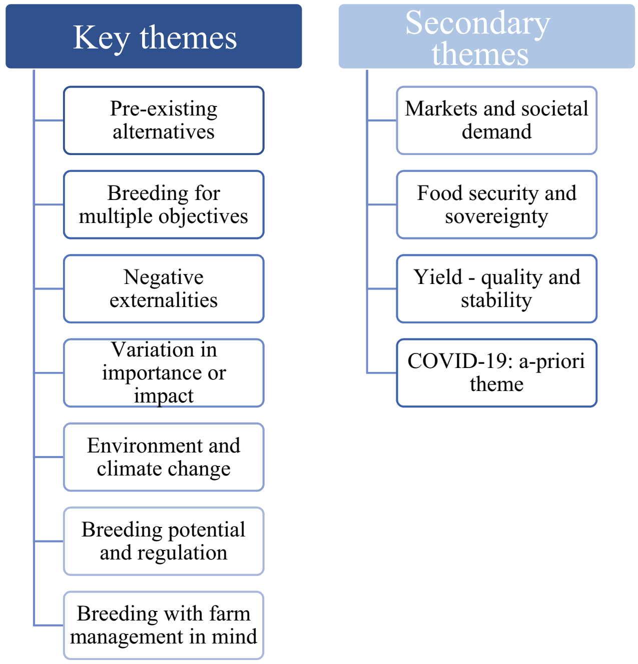

FIGURE 4 Overview of the key and secondary themes arising from the focus groups

food system. Such resilience was not specifically defined during the focus groups, but included discussion around maintaining yields, improving yield stability over the long term, coping with weather extremes and ensuring economic, social and environmental sustainability of food systems. (1) Pre-existing alternatives, such as improving soil or input management, were raised regularly. The importance of breeding was highlighted especially where farmers felt they lacked these pre-existing alternatives, such as where extreme droughts were anticipated due to climate change. (2) Breeding for multiple objectives and synergies and with practical concerns in mind was a preferred aim for future breeding programmes. (3) Negative externalities were raised as key concerns, such as the potential for reducing toxic compounds in crops to lead to a need for increased pesticide application. (4) Variation in importance or impact of specific breeding options across European regions, crop types and timescales were raised repeatedly, with breeding aims thought to be generally relevant (e.g. improving water, nitrogen and phosphorus use) often highlighted as more important than those of more regional concern (e.g. salt stress tolerance). (5) Environment and climate change impacts were common worries, particularly regarding extreme weather events, biodiversity loss and agro-ecosystem stability. (6) Breeding potential and regulation were highlighted as areas which needed to be considered both in terms of practicality (e.g. what cropboosting options are possible within the current regulatory framework) and futureproofing (e.g. potential for new plant breeding techniques in future and policy incentives for sustainable farming practices). (7) Breeding with farm management in mind was raised as a potentially important solution for improving agro-biodiversity and sustainability outcomes (e.g. through intercropping reducing pesticide applications). The goal, then, could be summarized as follows: targeted breeding which improves multiple traits which cannot be adequately managed by agronomic or societal practices, and which improves the resilience of the food system without trading off one benefit for another.

3.1 | Key themes

3.1.1 | Pre-existing alternatives

All stakeholder groups frequently raised the availability of pre-existing alternatives – a range of solutions, strategies or mechanisms which already exist and are available to actors to tackle a specific option's challenge – (or lack thereof) to contextualize why a given option was or was not important to them, with options that had pre-existing alternatives often being classed as less important priorities for breeding than options without such alternatives. Frequently raised pre-existing alternatives are summarized in Table 1. 'Improving plant water use' and 'Improving heat stress tolerance' were frequently raised by farmer representatives as being particularly important due to a lack of such alternatives and lack of control in existing farming strategies as illustrated by:

> It is [heat] stress...It is one thing that I cannot manage. ... it is the one that I control the least.
>
> Farmer representative #3

For some issues with geographical variation (e.g. water stress and salt stress), alternatives such as smart farming/farm management were discussed as useful for regions where these stressors were currently mild. However, in areas facing severe stress, these same issues were felt to be intractable problems which plant breeding could help to solve – participants encouraged research and policy to use 'both levers' to resolve these issues.

> ... the examples ... were all about breeding and they were all about certain methodologies of breeding, but I think that for certain of the topics the agronomy plays actually an important role.
>
> Farmer representative #6

The issues where agency was felt to be lacking varied across the groups, with farmers most concerned with heat and water stress, while policymakers were most concerned with heat, salt and phosphorus. The lack of concern around fertilizers from the farmer focus groups was driven largely by the current availability of such inputs – applying fertilizers was seen as a straightforward solution to the problem of nutrient management. NGO stakeholders did not specifically raise any issues as beyond our current abilities to manage, and instead focused on the options currently available to us, such as improving on-farm nutrient efficiency, and shifting diets towards more sustainable patterns.

> I don't think any of these [options] are important for human nutrition, because I don't think it's the plant's fault that we have malnutrition as a problem in Europe, be it lack of or too much. It is how we eat and what we choose to eat.
>
> NGO representative #1

3.1.2 | Breeding for multiple objectives

A common concern was that breeding programmes should aim to reduce trade-offs, and focus on breeding to achieve multiple important objectives simultaneously:

TABLE 1 Options identified as having pre-existing alternatives

Option	Pre-existing mechanism discussed
Digestibility of biomass	Processing
Increasing protein content and quality	Diet
Increasing antioxidants	Diet
Increasing vitamin and mineral content	Diet, Processing
Producing healthy omega–3 fatty acids in oilseeds	Diet
Decreasing negative and toxic compounds	Diet, Processing
Improving phosphorous uptake and use	Farm management
Improving nitrogen uptake and use	Farm management
Improving water use	Farm management

> I don't like this idea of prioritising. I tell you straight out I'm very much against so-called trade-offs when it comes to breeding progress. There shouldn't be. It is possible to have a plant that has improved nitrogen and phosphorous uptake.
>
> Farmer representative #9

Often, the multiple objectives to be aimed for were not explicitly stated, or were discussed in terms of how they would vary depending on region or crop (this theme of variation in importance is described further, below). However, several recurring combinations centred on:

- Coping with hot summers and low precipitation brought on by climate change – through a focus on heat and water stress
- Becoming more resilient to climate change through increased efficiency regarding inputs (nitrogen, phosphorus and water)
- Reducing inputs to meet EU goals by improving both nitrogen and phosphorus use

Multiple participants mentioned the importance of all (or nearly all) options within each goal category. Also, repeatedly raised was the need to consider the range of environments in which these crops will be grown and design a crop which: is resilient, balances sustainability trade-offs (such as reducing input use while maintaining yield), and which incorporates as many positives with as few negatives as possible, while considering the wider implications for agro-ecosystems and populations of crop wild relatives.

> We all know that many of the genetic improvements or alterations we have done in crops, they came with a cost, like is it taste, or vitamins, or...more diseases or whatever? It always had a drawback on one side.
>
> Policy stakeholder #1

A few specific areas where trade-offs could easily occur were mentioned:

- Increasing yield but decreasing quality (flavour, nutritional content, etc.)
- Reducing toxic compounds but increasing pest/disease susceptibility
- Increasing yields at the cost of sustainability and resilience
- Crop or region-specific trade-offs (described in more detail, below)
- Land use change and potential negative implications for the socio-economic status of rural communities
- Farm management, including harvesting, storage and a lack of breeding programmes targeting the longer term needs of perennial and agroforestry crops

3.1.3 | Negative externalities

Participants highlighted a list of negative impacts that could arise from plant breeding options. These were highly specific to the option being discussed and ranged from issues relating to broader impacts on the agro-ecosystem (such as the potential for altering the growing season to mean materials, such as food and habitat are not available to insect and bird species who rely on them at key points in the season); knock-on negative consequences for the crop itself (e.g. if breeding for improved digestibility of crop biomass led to a reduction in lignin, and therefore an increase in lodging); problems for food harvest, storage and processing (e.g. breeding for larger harvestable parts causing problems with mechanized harvesting and processing procedures); and other issues relating to sustainability more broadly, including impacts on land use change, food supply and demand and resilience to climate change.

> … shifting the growing season, which I do not know what the effect will be on… the ecosystem and insects or whatever that are dependent on the crop in a particular period…
>
> Farmer representative #1

This theme highlights the importance of assessing potential negative consequences, and engaging with stakeholders to identify and understand these, prior to committing to specific breeding aims or objectives. Four options specifically discussed in relation to negative potential impacts are summarized below in Table 2. Three of the four options identified as having negative externalities belong to the Yield category, suggesting that particular care may need to be taken to consider the broader ramifications of a breeding focus on yield. While ecosystem and biodiversity impact concerns were broadly shared across stakeholder groups, farmer representatives were also concerned that with plants with larger harvestable parts the entire processing chain would need to adapt to accommodate these new products not only at harvest but also for storage and processing of crops to create food products.

> The least important is increasing the size of harvestable parts. At this moment, I see it as a nonsense because you need to go all along

TABLE 2 Options participants specifically related to particular negative externalities

Potential negative impacts in relation to:	Options: Altering growing season of plants	Increasing the size of harvestable parts	Reducing negative and toxic compounds	Improving digestibility of biomass
Consumer expectations		■		
Ecosystem impacts and biodiversity	■			
Pests and disease	■		■	■
Crop harvest, storage or processing	■	■		
Resilience to weather				■

TABLE 3 Scales at which impact and importance of options were thought to vary

Option	Regional (within Europe)	Crop	Temporal	Global vs European
Improving salt stress tolerance	■	■	■	■
Improving plant water use	■	■	■	
Altering growing season of plants		■		
Increasing the size of harvestable parts		■		
Improving heat stress tolerance	■	■	■	
Improving nitrogen uptake and use	■	■		
Decreasing negative and toxic compounds		■		
Improving digestibility of biomass	■	■		■
Improving photosynthesis	■			■
Increasing vitamin and mineral content				■
Increasing protein content and quality			■	■

> the processing chain to adapt the technology if you have a bigger harvestable part.
>
> Farmer representative #8

3.1.4 | Variation in importance or impact of breeding option

A strong theme arose in relation to variation in the importance or impact of particular options across geographical regions, temporal scales and between different crops. Five options were specifically discussed as being very important, either in terms of their importance to all crops, all European regions or both: 'Improving Nitrogen uptake and use', 'Improving Phosphorus uptake and use', 'Improving plant water use', 'Improving heat stress tolerance' and 'Improving photosynthesis'. These options were seen as being generally applicable across agricultural systems, and therefore of higher overall importance to European agriculture.

However, all 15 options were also considered by at least one stakeholder to be of differing importance when considered at different region/crop/temporal scales. Certain options were thought to be of relevance to specific European regions, or local contexts (e.g. salt stress being of importance to parts of the Netherlands), while others were considered to vary in importance based on the crop (e.g. increasing the size of harvestable parts was thought to be less relevant for those crops where this would present a bio-physical problem, such as apples), or temporal scale (e.g. the increasing importance of plant-based protein produced within Europe in the coming years) – see Table 3, below, for an overview.

> There is one aspect I would like to stress, which is really important. We have to keep in mind that different regions have different

> needs and different characteristics. When we talk about sustainability we tend to use a general European concept that cannot be applied the same way in the northern, in the centre or in the southern parts.
>
> Farmer representative #1

Participants also noted differences in needs for the global market, particularly referencing developing country contexts versus the European market, highlighting the fact that Europe imports and exports both technology and food, and that plant breeding should aim to benefit both European and global agri-food chains.

3.1.5 | Environment and climate change

Stakeholders raised grave concerns around the impacts of more extreme weather events, in particular droughts and heat waves, on food production:

> So the probably upcoming effects of climate change and the desertification of many places in the European Union. That will be something important to consider, important.
>
> Farmer representative #10

Several participants shared their experiences of drought stress (often in combination with heat stress), and the widespread crop loss that followed, and while management strategies, such as irrigation, insurance and sharing risk through farmer co-operatives were raised as potential ways of mitigating the impacts of drought, it remained a key concern for participants. Other climate change impacts which stakeholders repeatedly raised included the emergence of new pests and diseases, and the general uncertainty surrounding the future and need for resilience.

Sustainable land management and the need to sustainably produce sufficient food was often cited alongside issues of efficiency and circular farm management. The need to reduce inputs (fertilizers, pesticides and water) both in order to meet European goals and to reduce the carbon footprint and/or improve the sustainability of food production in general was highlighted. The use of land for food production was generally seen to be more important than for biofuel production, with calls from NGO and policy stakeholders in particular to avoid widespread biofuel production:

> ...Biofuel use or biomass in general should be very, very limited, or is very limited, in sustainable future energy scenarios.
>
> NGO representative #2

3.1.6 | Breeding potential and regulation

The potential of plant breeding to accomplish the option aims, whether through traditional breeding methods, new plant breeding technologies or GM was not always thought to be straightforward. Opinions were raised both for and against the mainstreaming of new plant breeding technologies and GM, with a frequently raised issue around practicality:

> The only issue I have with all these ... there is talk about breeding techniques ..., how accessible will these breeding techniques become to European breeders and ultimately to the European farmer's toolbox?
>
> Farmer representative #9

Issues around agricultural and plant breeding policy were raised in relation to new plant breeding technologies and GM (both for and against), policy incentives for sustainable farming and food system practices, including a focus on sustainable nutrition, along with a number of concerns regarding issues of intellectual property rights and breeding, including avoiding linked treatments and ensuring seed saving remained legal:

> ... relating the whole question of accessibility of plant reproductive material for farmers. Now this is of course relevant with regards to patent protection... also if we think about the farmer's privilege to save and reuse seeds for own purpose.
>
> Farmer representative #2

3.1.7 | Breeding with farm management in mind

Agronomy and farm management were raised not only as alternatives to plant breeding, but also as key areas of focus for future plant breeding efforts. Several specific examples were given of the utility of breeding to improve agrobiodiversity, including through breeding varieties to be intercropped, and breeding for single-species variety mixtures.

> As intercrops and mixed cropping actually are shown to be quite an impactful way of growing for improving the sustainability of the farming systems, ..., but, if you miss the right cultivar for mixing, then it's not easy to boost this type of agronomic management.
>
> Farmer representative #6

Additional comments included the need to breed for soil health and quality, breeding crops well suited to precision and smart agricultural practices, and breeding with the full system, including pest and nutrient management, in mind.

3.2 | Secondary themes

3.2.1 | Markets and societal demand

Consumer preference was highlighted as an important factor to bear in mind when choosing plant breeding targets, although tensions between who the buyer actually consisted of and the ability of consumers to influence those were raised:

> But the fact is that the market for the plant breeders, well it may look as if it is the growers, but in fact…[i]t is the processors, the buyers from the growers that determine.
>
> Farmer representative #1

The importance of end markets, and bearing in mind the intrinsic international markets involved in import and export to/from Europe were highlighted, with concerns raised around the competitiveness of European agriculture on the global stage, as well as the responsibility Europe had to produce foods or seeds for export which meet global needs as well as local ones. NGO and policy representatives also highlighted the need to consider the true cost of food production and re-evaluate pricing practices to reflect these accurately.

3.2.2 | Food security and sovereignty

Issues around the need to ensure adequate production of key foodstuffs, particularly plant-based protein products, from within Europe, rather than relying on imports from other countries were highlighted both in terms of creating a food sovereign future and in mitigating the perceived issues around being able to import GM crops but not being able to grow them widely within Europe.

> A lot of young people now and in 30 years' time will probably be [vegan]… As long as we have a big import of soya for food and feed that is not a big problem I would say. But if you want to be self-sufficient on protein that is of course a big problem.
>
> Farmer representative #4

3.2.3 | Knowledge transfer and exchange

The need for more integrated knowledge transfer, exchange and education was raised in relation to several topics, including: engaging in an open and informed debate regarding GM and new plant breeding technologies (whether for or against); the need for plant breeding programmes to take into account the full supply chain; the need for discussion between all actors in the food system, including farmers, policymakers, the public and scientists.

> I think the supply chain should be more involved in developing sustainable production systems. It should be a joint responsibility and you should not talk about resilient production systems. You should talk about resilient supply chains.
>
> Farmer representative #1

3.2.4 | Yield – quality and stability

While yield was considered an important trait, concerns were raised that certain options for increasing yield quantity (particularly 'Increasing the size of harvestable parts') might lead to reduced yield quality characteristics, thus having a net neutral or negative impact on output and profitability. In addition, farmer representatives felt strongly that the goal for yield should be to achieve yield stability, rather than an increase in tonnes per hectare, in order to future-proof production systems:

> In my perspective, the yield itself, it's not really the major issue. The major issue, in my vision, it's yield stability in the longer term. That's what farmers look for, and that's what the objective should be when we think to sustainable systems, in my opinion.
>
> Farmer representative #6

3.2.5 | COVID-19: a-priori theme

All comments referring specifically or obliquely to COVID-19 were coded to a pre-defined a-priori COVID-19 theme, to understand thoughts around this crisis and its impact on food systems. Concerns tended to focus on the uncertainties surrounding the long-term impact of COVID-19, impacts on purchasing and cooking and problems with worker safety and worker availability for farm labour:

> I make a link with what is happening now [COVID-19 travel restrictions], where farmers cannot harvest their production with no workers from Morocco or east side of Europe.
> Farmer representative #11

3.2.6 | Option Card #16 results

After participants discussed all 15 option cards, they were given a chance to highlight possible options that they felt were important for future proofing Europe's crops through an activity called "Option Card 16". Participants during this activity mentioned several possible options; however, they found it difficult to build consensus around one as the most important. Presented here is a summary of the key issues raised in these discussions – in the interest of brevity and clarity, only those issues which were raised multiple times and are not discussed in the general themes above are shown in Figure 5. It is worth noting that biotic stress and smart farming are outside the CropBooster-P project scope, thus their exclusion from the 15 cropboosting options presented.

4 | DISCUSSION

The importance of preparing European food systems to cope with climate change and future stresses through a combination of breeding more resilient crops, reducing the use of inputs and sustainable land, farm and consumer practices were highlighted throughout the focus groups. The need to avoid negative externalities and to reduce trade-offs in plant breeding, and to find ways of achieving all three goals in tandem was a key message. Stakeholders were particularly concerned about the potential for yield increases to co-occur with produce quality decreases – multiple participants gave the specific example of this having been seen in tomato breeding; a perception confirmed by Tieman et al.'s (2017) observation that modern commercial tomato varieties contain significantly lower amounts of key flavour compounds and identification of genetic targets for reversing this loss of taste. Others raised concerns around yield being prioritized over sustainability, particularly in relation to pesticide use, with one specific example being cited of Brussel sprouts bred for reduced bitterness being more vulnerable to pests. Extensive research has focused on the effects of glucosinolates – a class of defence compounds with a bitter taste, reduction of which has been a focus of breeding in brassicas to increase consumer appeal (Drewnowski & Gomez-Carneros, 2000) – on pest dynamics. Efficacy of glucosinolate defence against pests varies, leading to calls for plant breeding research to focus on glucosinolates as a mechanism for increasing insect resistance (Hopkins et al., 2009). Resilience, including yield stability over the longer term, was also highlighted as an issue which should not be traded off – a finding which echoes previous farmer engagement work (Asrat et al., 2010; Macholdt & Honermeier, 2017).

Stakeholders highlighted that the cropboosting options will have variable importance and impact depending on the region and context in which they are deployed. Variation across geographical regions (e.g. based on different climates, soils and food systems) were noted as important considerations. Temporal variation was also discussed, both in terms of short vs longer term needs for sustainability (e.g. the need for more protein security and resilience to weather extremes in the future), and in terms of differing needs within the growing season. This reinforces previous findings that agri-food professionals from different food systems prioritize food system challenges and solutions differently, depending on their regional contexts (Dengerink et al., 2021). Variation in importance from crop to crop was also a key theme and highlights the importance of developing relevant resilience traits, such as drought tolerance and nutrient use efficiency, in a wide range of important crops in order to ensure sustainability in the long term. Of the 15 cropboosting options presented, 14 were selected as 'most important' by at least one stakeholder, and 11 were selected as 'least important' by at least one stakeholder, further highlighting the variation in importance of each crop improvement option to different stakeholders. Only a small subset were selected as 'most important' by at least one stakeholder and not

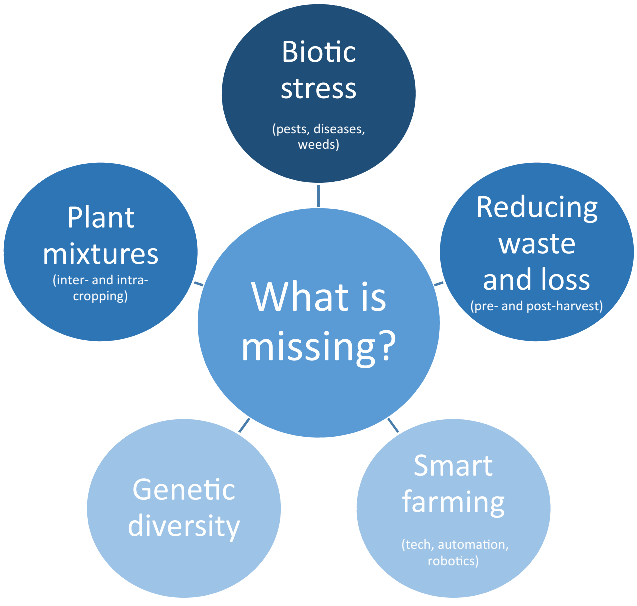

FIGURE 5 Key themes arising from Option Card 16 Activity (Darker blue corresponds to a theme being more frequently mentioned)

as 'least important' by someone else – 'improving plant water use', 'improving heat stress tolerance' and 'improving protein content and quality'. This further underscores the importance of the 'Variation in importance or impact' theme as two of these (water use and heat stress) had been specifically raised as being applicable in a wide range of agricultural systems and contexts.

Negative externalities were raised as concerns, including that breeding might meet specific targets (e.g. yield increases) but not meet consumer expectations, or not in ways which are compatible with crop harvest, storage, processing systems or sustainability goals. As these will vary depending on the crop and system of interest, it is beyond the scope of this paper to quantify the impact such trade-offs might have on a European scale, though the importance of appropriate crop load management for apple quality, yields and orchard health (Suo et al., 2016), for example, suggest such considerations will be relevant for certain key crops. Agro-ecosystem impacts, including ecosystem degradation due to input use (e.g. nitrification of water bodies, reduced soil quality and air pollution), and loss of biodiversity were real concerns to stakeholders and should be taken into consideration for future breeding priorities. Increased incidence and/or severity of diseases and pests was a further concern, particularly regarding those breeding aims which might compromise certain defence mechanisms of the plant. Ongoing research into plant volatile compounds and natural systems which repel pests may help plant breeding programmes to avoid losing such important attributes, particularly in light of the expected large-scale spread of key pests and diseases due to climate change in the coming decades (IPPC Secretariat, 2021). Integrated or systems-based breeding approaches (Lammerts van Bueren et al., 2018), bringing insights from farmers into the breeding process, could help to identify and avoid potential trade-offs early on in the breeding process.

The potential of plant breeding to improve agrobiodiversity through breeding with farm management in mind was raised in relation to both intercropping and single-species variety mixtures. Benefits from intercropping are wide-ranging, including improving and maintaining soil health, reducing water runoff and erosion, improving nutrient acquisition and utilization including increasing nitrogen availability (Glaze-Corcoran et al., 2020), reduced weed pressure (Liebman & Dyck, 2014), reduced pressure from pests and pathogens and yield and economic improvements (Dowling et al., 2021). Variety mixtures in wheat, meanwhile, have been found to have significantly higher yields than their monoculture counterparts, particularly in situations with high disease pressure (6.2% overyielding) (Borg et al., 2018), suggesting that focusing breeding efforts on these areas could have significant benefits for both yields and agricultural sustainability. While the farm level need analysed in this paper broadly focused on the current crop portfolio, one particular issue of relevance has not been discussed – namely, the potential for crop diversification through integration of novel or under-utilized crops, which may be of interest for novel intercropping pairs as well as more general diversification of cropping systems. In particular, pulse crops could provide a useful source of plant protein, which was raised as a concern by stakeholders in terms of future food security in Europe due to dietary shifts. Work in this area would have implications in terms of research investment, and setting up new or further developing existing value chains for orphan crops, but could provide sustainability benefits and additional options for paired crop breeding programmes.

Questions about the potential for plant breeding to achieve the aims presented were raised, particularly in relation to what would be feasible within the context of European (or UK) regulations. Several participants noted the differences in which types of new plant breeding techniques were allowed in Europe as compared with other parts of the world, such as the US and China, particularly the lack of approval for genetically modified commercial crops in the EU, and the ongoing debate regarding whether various new plant breeding techniques should be classified as genetically modified organisms (Van Der Meer et al., 2021). Although these regulations are the subject of ongoing consultation in the EU (European Commission, 2021), the potential for gene-edited crops to find easier paths to market than first-generation biotechnologies does not itself guarantee the social approval needed to ensure their success (Anders et al., 2021; Borrello et al., 2021). Increased education and knowledge exchange regarding agriculture and plant breeding were widely recommended as means to encourage better policies, research and action, although participants' stances on genetic modification and new plant breeding techniques varied.

Participants did note the potential for plant breeding to contribute to sustainability through pathways including: reducing input use and thus environmental degradation; increasing yields and improving food security and sovereignty; and increasing resilience to extreme weather events, particularly drought and heat waves. Progress has, indeed, been made on each of these areas in plant breeding in recent years (e.g. (Hu & Xiong, 2014; Li et al., 2018; Steffen Noleppa, 2021)), but this remains a space for active research.

Stakeholders, then, shared a concern with using plant breeding primarily to future-proof against areas where they currently lacked agency, including to cope with climate change by developing crops which are highly resilient and which combine a number of positive attributes (rather than being focused on one single trait) in order to ensure more sustainable food systems for the future.

5 | RECOMMENDATIONS

Based on these focus group discussions with stakeholders of relevance to agricultural production, we make the following key recommendations for breeding programmes to future-proof European food systems:

1. Crop breeding should focus on the issues which are most difficult to fix in-field with altered farm practices or on-plate through different dietary habits.
2. Closer collaboration is needed between crop breeding and agronomic scientists and experts in order to identify and reduce trade-offs from breeding programme outputs.
3. Trade-off analysis should be explicitly incorporated into crop breeding research, with broader food system impacts considered (e.g. suitability for market) alongside sustainability concerns.
4. Breeding programmes should avoid an over-emphasis on yield increase as a primary outcome, as other factors such as storage and processing also affect farm income and profitability; yield stability across years, by contrast, remains an important aim for breeding.
5. Breeding programmes should aim to incorporate multiple benefits in order to increase food system resilience and sustainability.

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